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ANALYSIS OF EFFECTS OF IMPURITIES INTENTIONALLY INCORPORATED
INTO SILICON

JPL Contract 954694

Final Report

For Period Covering

1 February 1977 through 1 December 1977

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ABSTRACT

A methodology has been developed and implemented to allow silicon samples containing intentionally incorporated impurities to be fabricated into finished solar cells under carefully controlled conditions. The electrical and spectral properties were then measured for each group processed, and this data, along with all the material, (cells and scrap) were delivered to JPL for further analysis. All 33 lots of Group "C", 14 lots of Group "CM" and 16 lots of Group "F" have been fabricated into cells, tested and delivered to JPL.

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1.0 SUMMARY

Sixty-three lots of silicon sample wafers derived from single crystal ingots provided by three different sources, have been fabricated into solar cells using conventional aerospace process technology. The three sources of the silicon material studied were: 1) Dow Corning/Westinghouse crucible grown silicon (the "C" group), 2) Monsanto crucible grown silicon (the "CM" group), and 3) Monsanto float zone silicon (the "F" group). These groups of wafers contained various types and concentrations of impurities deliberately incorporated into the silicon during the growth of the crystal. A processing procedure was developed and implemented which monitored process control and exposed any cross contamination from run to run. This sequence was used for all runs made.

The properties of the cells within each group were extremely consistent, except in one group where two cells showed possible polycrystalline structure, both electrically and spectrally. There was a significant amount of variation from group to group, which was not unexpected. There was good correlation between the electrical outputs as measured and the spectral response data. Air Mass Zero short circuit current densities ranged from a low of 13.9 (Group 7 CM) to a high of 34.9 mA/cm² (Group 13-F), and power output densities varied from 5.6 (Group 8 CM) to 16.7 (Group 14F) mW/cm². A typical space cell made from "high grade" silicon of this thickness and nominal 2 ohm-cm resistivity yielded 15 to 17 mW/cm² using this process sequence, thus indicating that some of the sample groups were not compromised significantly by deliberate impurity contamination.

2.0 INTRODUCTION

The purpose of this program was to investigate the effect of deliberately incorporated amounts of known impurities into silicon which was then sliced and used for the fabrication of

solar cells. This was accomplished by manufacturing solar cells from this type of material using the typical processes and procedures employed for space flight devices. Each group of material was independently handled using formal control procedures in order to fully document the processing. Each group of finished cells was electrically and spectrally characterized in order to form a data base for the analysis.

3.0 TECHNICAL DISCUSSION

All sixty-three groups of JPL supplied silicon slices have been fabricated into solar cells using a standard processing sequence. In order to insure that there was no cross contamination from run to run it was necessary to establish a monitoring procedure that would alert us to such an eventuality. This was developed and put into practice at the onset of the program, and all evidence indicates that there has been no unintentional contamination introduced into any group processed.

3.1 Monitoring Scheme

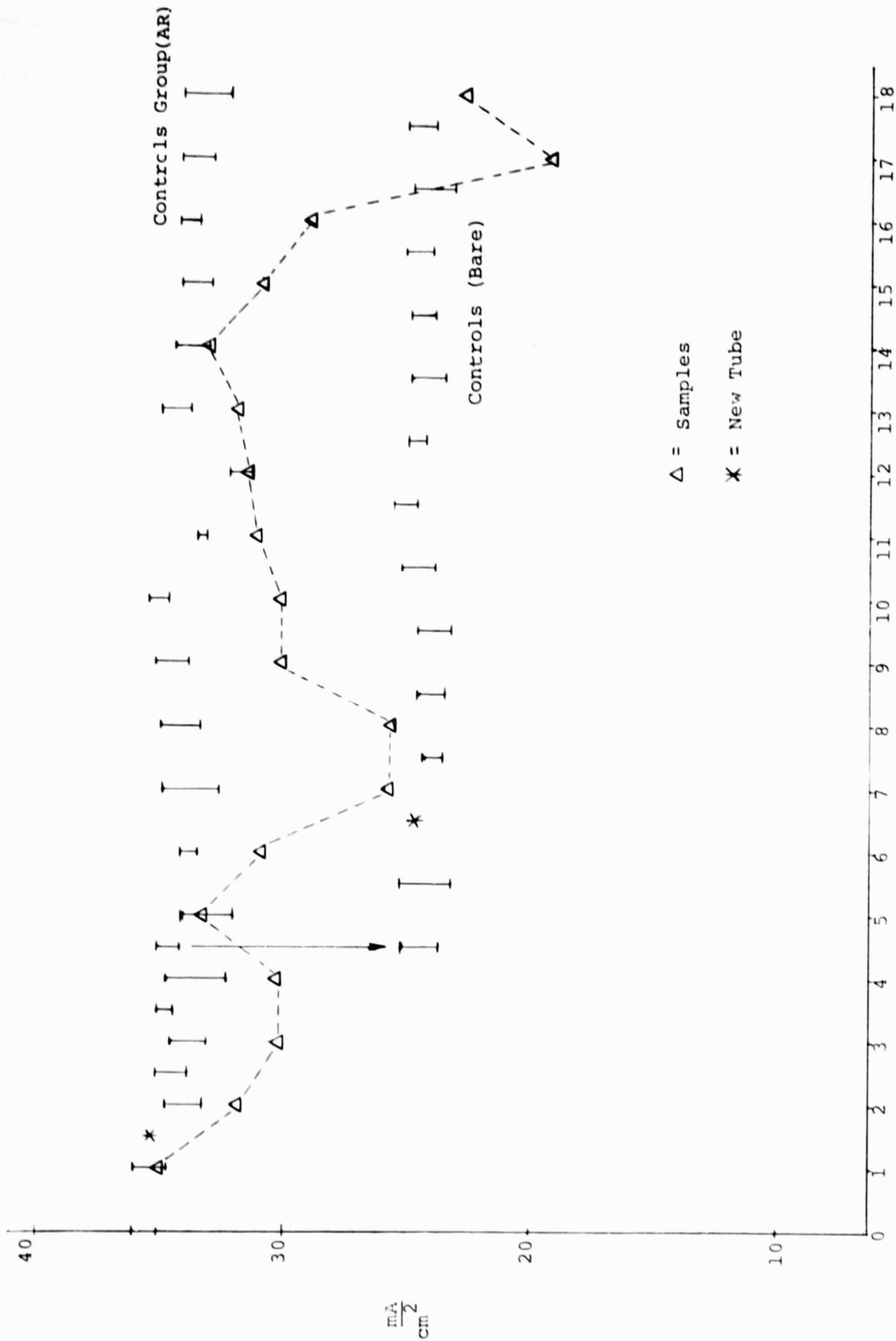
A dual monitoring sequence was employed to control any unwanted contamination. Prior to processing any of the sample groups a set of control cells, using standard silicon slices supplied by the Spectrolab crystal growing facility, was fabricated into cells using the baseline production method. These cells were electrically and spectrally characterized and this data was used to monitor the subsequent control cells that were fabricated. The same procedure was used on the baseline silicon slices supplied by JPL and this data was used as a comparison base for all lots in the group. The Spectrolab control silicon slices were nominal two ohm-cm (1-3) which was slightly lower than the measured values of resistivity (2.5-6.0 ohm-cm) in the "C" group

and slightly higher than the resistivity (0.15-1.15 ohm-cm) of the "CM" and "F" groups.

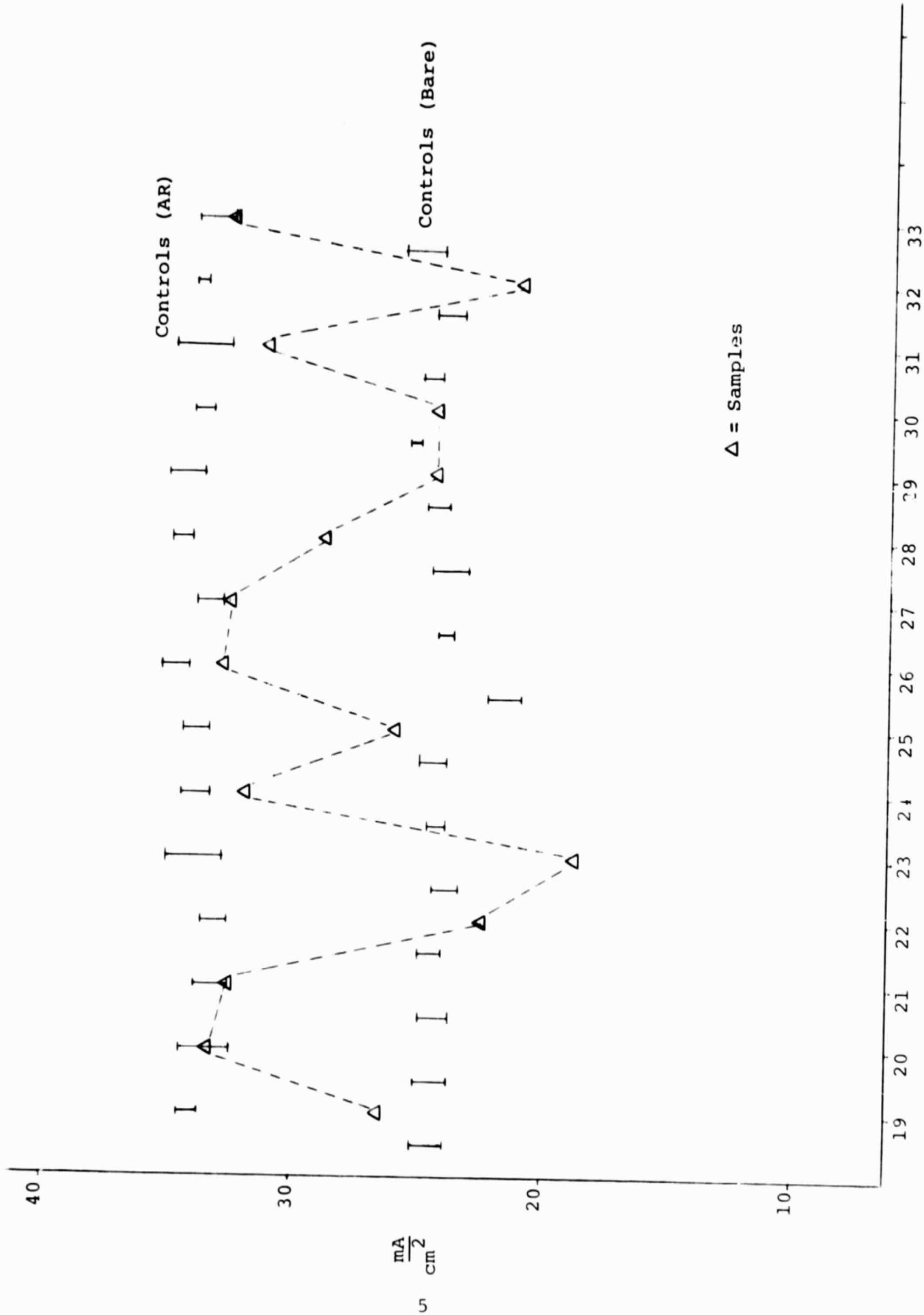
The second monitoring scheme was employed during the high temperature diffusion and contact sintering process steps. At the diffusion step, six control slices of Spectrolab grown silicon were placed on the diffusion boat along with the JPL samples; two cells were placed at the front of the diffusion boat in reference to the phosphine gas flow, two were within the JPL supplied sample group and two were at the back of the boat.

The identity of these six control cells was then maintained throughout the remaining process steps. The same cell arrangement was maintained during contact sintering process although sintering temperature was some 250°C below diffusion temperature. After this test group was evaluated, another set of Spectrolab control cells were fabricated in freshly cleaned diffusion and sintering tubes. This set of controls was then compared to both the initial controls and the previous sample run controls. The next JPL sample group was not started into the processing until all cell characteristics indicated that no contaminants from the previous sample group were affecting these control cells.

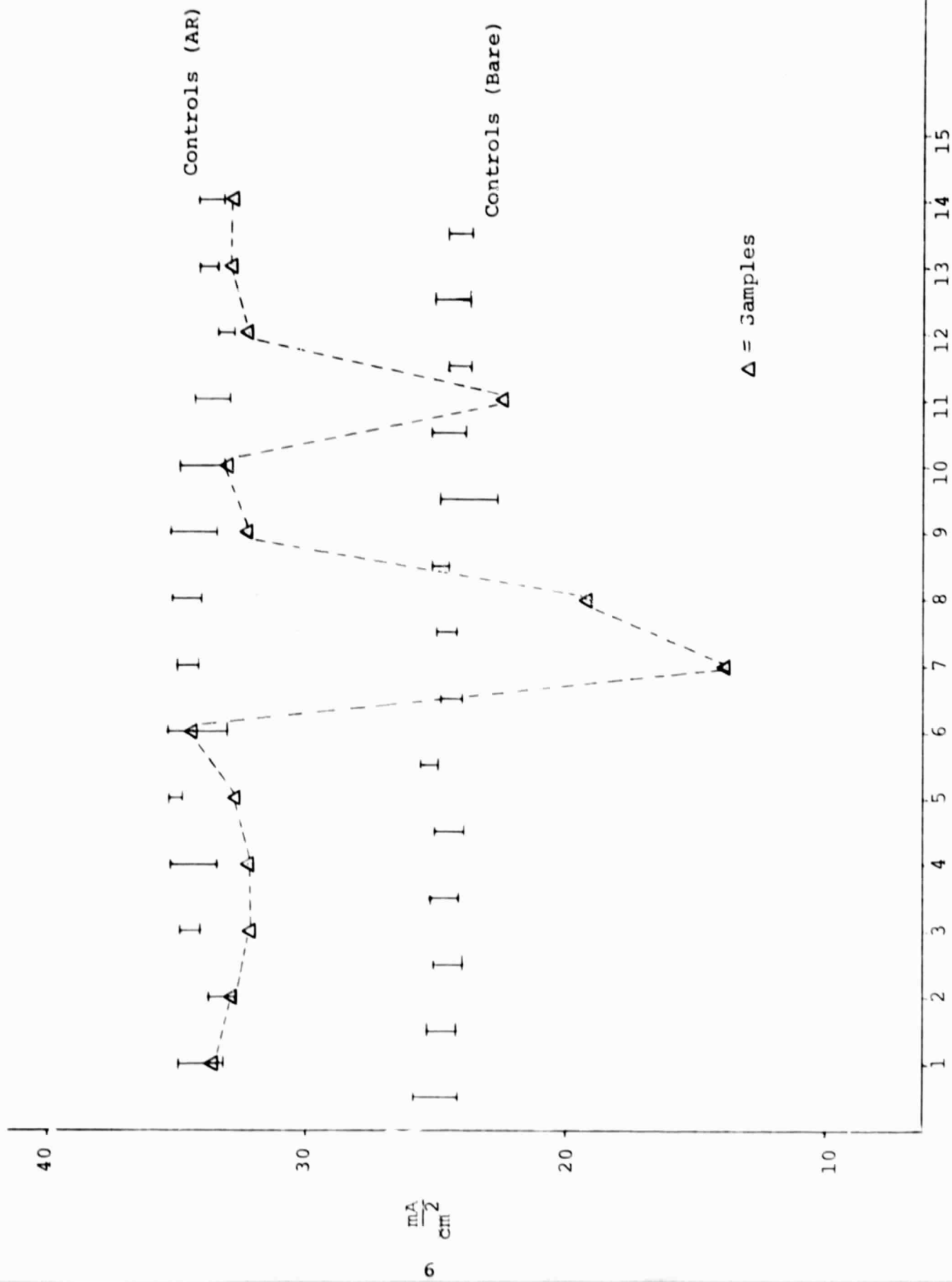
Figure 1 is a plot of the short circuit current density of all of the control group runs in our program. It will be noted that between runs 4 and 5, not all the control cells were fabricated using AR coatings because of scheduling problems. However, this group was split into AR and "bare" cells to provide a baseline comparison that was traceable to the original AR coated controls. The range rather than the average value of current density is plotted to indicate the normal distribution between cells in a given group. The variations in current density are attributable to differences in gridline width, junction



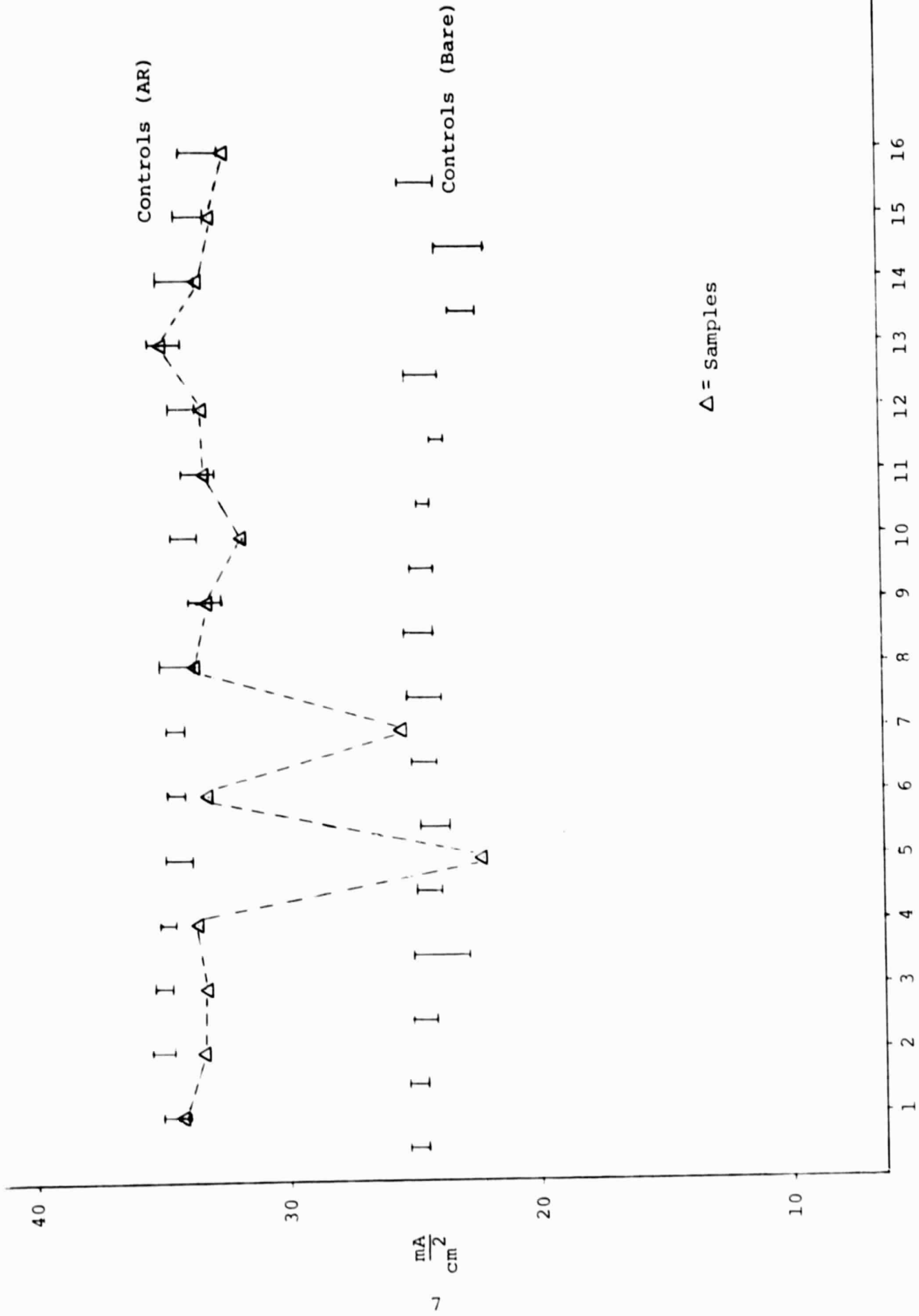
Process Run, Group "C"
Figure 1. Current Density, Control Group



Process Run, Group "C"
Figure 1 (cont'd.) Current Density, Control Groups



Process Run, Group "CM"
Figure 1 (cont'd.) Current Density, Control Groups



$\Delta = \text{Samples}$

Process Run, Group "F"
Figure 1 (cont'd.) Current Density, Control Groups

depth, cell thickness and silicon material resistivity. Based on our experience at Spectrolab, the variations observed are within the expected limits. For comparison, the average short circuit current densities of the test groups are also plotted.

3.2 Process Sequence

The wafers supplied from JPL were in two configurations. The "C" group silicon slices were "as-cut" round wafers approximately 32 mm in diameter, while the "CM" and "F" groups were "nominal" 2 x 2 cm slices with one side polished. Since these wafers were only polished on one side, the standard Spectrolab polish etch processing was included to remove any saw damage from the "as cut" side. Therefore all the slices were polish etched in a solution of nitric, hydrofluoric and acetic acid to remove the cutting damage. The final thickness of these samples, and for all control slices, was $0.20 \pm .025$ mm. The "C" group slices were then diced into 1 x 2 cm configuration while the "CM" and "F" groups were 1.85 x 1.85 cm, and the Spectrolab control slices were 2 x 2 cm. A Tempress 602 dicing saw was used in all cases. All scrap silicon pieces and any cell that fractured during processing were saved and sent to JPL, identifying the group it belonged to, along with the balance of the electrically tested cells and electrical data.

The samples and control cells were then diffused using phosphine as the dopant source. The temperature used was 850°C and the time schedule was designed to yield a sheet resistance of about 45 ohms/square or a diffusion depth of approximately 0.4 microns. After diffusion, the wafers were back etched to remove the junction from one side. Some cells were broken or damaged in this operational step, however, this occurrence was relatively rare and the impact on yield was not significant.

The samples were then contacted using evaporated silver-titanium, where "N" contact utilized a 9 gridline per cm basic design. The cells were then sintered in a clean sintering tube to assure good ohmic contacts, AR coated using vacuum deposited tantalum pentoxide and edge etched to eliminate any metal over-spray that would act as a shorting path. The completed cells were then tested electrically at 25°C under a Spectrosun^R Mark III calibrated xenon light source at AMO (Air Mass Zero) intensity of 135.3 mW/cm². All test data are given in terms of total area, except in the case of spectral response data, and since the contact pattern covers approximately 7.5 percent of the cell area for the 2 x 2 cm, 10.1% for the 1 x 2 cm cell and 8.5% for the 1.85 x 1.85 cm cells, this data can be converted to active area very readily.

An I-V power curve was taken for each sample and control cell. From this curve the short circuit current (I_{sc}), open circuit voltage (V_{oc}), curve fill factor (FF), maximum power (P_{max}) and conversion efficiency (η) was recorded. The cells were then tape tested to verify that the contacts were adherent and therefore not influencing certain electrical parameters such as FF, P_{max} and η . This operation was done after the electrical tests so that even if the contacts were not ideal, as was the case in some groups, useful information about the electrical properties of the cell could be obtained that would otherwise be impossible if the cell contacts, or the cell itself, were not intact.

Spectral response in terms of $\mu A/\mu W$ was then taken for each sample cell and a portion of the control cells. In addition, dark forward and dark reverse measurements were also made. After reducing all the data, the sample cells, plus all scrap material were packaged, identified and shipped along with a copy of the data packet to JPL for further analysis.

3.3 Test Results

Initially, the test results obtained for the various groups of cells had no significance at all since Spectrolab did not have any information on either the impurity dopant or its concentration level. The only criteria we could observe was that one group had a higher conversion efficiency compared to that of another group or to the baseline group. It could be concluded, however, that many of the sample groups had rather impressive power outputs that were comparable to cells made from "high grade" silicon.

After receiving the impurity dopant list correlating group identification number to the various impurities and their reported concentration levels, it was evident that certain elements degraded cell conversion efficiencies quite drastically, even in relatively small quantities, while others showed little or no effect with varying impurity levels. Among the elements that did cause a definite efficiency degradation were aluminum, chromium, iron, nickel, titanium, vanadium and zirconium. However, except for titanium, zirconium and vanadium, even these elements, at levels below 10^{13} atoms/cm³ did not cause drastic degradations. Since much of the impurity level data was sketchy (i.e., indicated only as "less than" or "more than" a given amount, was listed as nondetectable or was not listed at all) the best we could do was to only give general correlation of data between the various groups. Those elements that showed less than a 10% degradation of cell efficiency at various concentration levels were manganese, magnesium, carbon and sodium. It was thought initially that copper, in combination with degradation causing elements, tended to neutralize the harmful effect of the second impurity as shown in Figure 2. However at the Task Integration Meeting, held at California Institute of Technology, December 8, it was learned that a possible mixup of cells for the

EFFECT OF COPPER

<u>Impurity</u>	<u>Concentration</u>	<u>% Reduction</u>	<u>Source *</u>
Copper	1.7×10^{16}	0.7	W/D
Titanium	7.0×10^{13}	39.0	W/D
Copper/Titanium	1.3×10^{15} / 3.6×10^{14}	0.7	W/D

* \equiv Westinghouse/Dow Corning

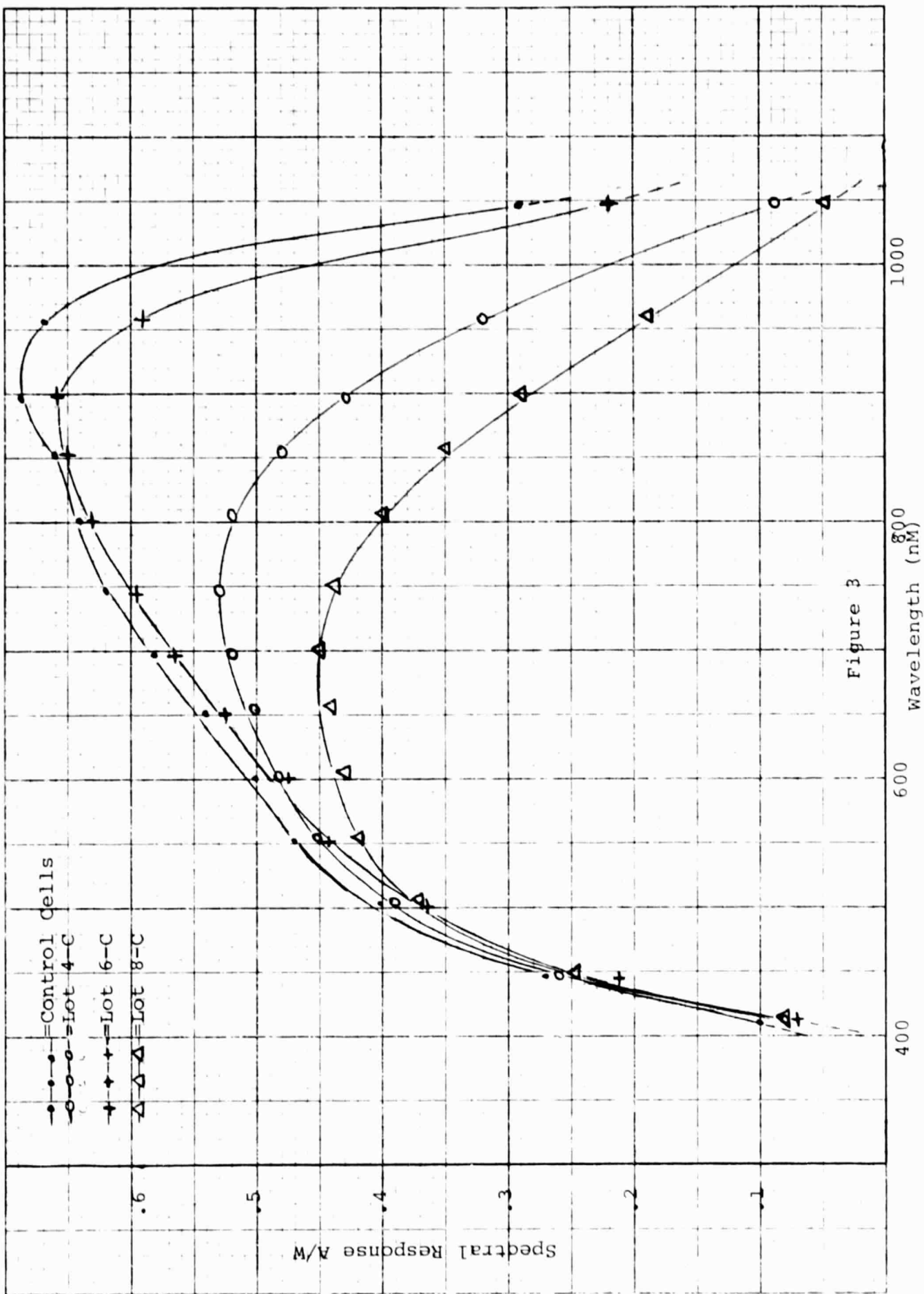
Figure 2

Cu-Ti group may have occurred and there was uncertainty as to the actual identity of the impurity. A repeat of this experiment by growing a second ingot is now in process by the supplier and data obtained from this new material should clarify our findings. Until such findings are made available, no additional comments will be made on this phenomenon.

Figure 3 is a plot of spectral response curves representative of the typical cell in the groups shown. In addition, a plot of the spectral response of a typical control cell is included for comparison. There appears to be very good correlation between the measured current density and the spectral response curves for all groups measured. As would be expected, the impurities degraded the long wavelength response of the cell because this region is influenced by the minority carrier diffusion length (L_n) which would be sensitive to impurity effects.

No correlation could be made between cell output or fill factor and the measured values of the dark forward and reverse currents for the cells. Measurements were made at one volt in the reverse direction and at approximately 0.5 volts in the forward. This data was taken at room temperature.

Most groups were routinely processed with no difficulty. On a few groups, a light "haze" covered the sample group cells while in other cases the sample groups plus the control cells diffused on the same boat both exhibited "haze." However, this "haze" disappeared from the cell surfaces in the contact evaporation pre-cleaning step, done just prior to loading cells into the vacuum chamber. Apparently no contamination occurred to affect either the silicon surface or electrical characteristics as the contact adherence test showed good metallization adherence and electrical parameters on most lots remained good.



The group with a high nickel content, Lot 25-C, became severely "pitted" when polish etched in the standard $\text{HNO}_3 \cdot \text{HF} \cdot \text{CH}_3\text{COOH}$ etchant solution whereby approximately half the cells were lost in fabrication. No tape peel test for contact adherence was performed on this lot as the initial cell tested, broke in the tape peel machine. A second lot in the "C" group, Lot 32-C which contained a ternary mix of chromium, iron and titanium, also showed some evidence of "surface anomalies," but the effect was minor with regard to cell loss. However this group showed a severely reduced power density of only 8.5 mW/cm^2 .

New tooling was designed and purchased to accommodate the "nominal 2 x 2 cm" cells after a check of the cells in the "CM" and "F" groups indicated tolerances of cell dimension exceeded the tooling tolerances Spectrolab had available. To provide the least amount of variation in processing, all cells in these two groups were diced to a 1.85 x 1.85 cm outside dimension, which gave us the maximum size attainable from the wafers supplied since only $\sim .025 \text{ cm}$ was diced off each side of the cells after the normal chemical etch/polish process.

Initial lots, when tested electrically, showed that a large percentage of the cells were "shunted," exhibiting poor fill factors. Controls that were run simultaneously with these groups showed good electrical characteristics. When control cells cut to the sample sizes also showed good results, a close check of the test setup was made. Our finding showed that cells fabricated from the new groups, had ohmic bar float dimensions of 0.03 cm compared to Group "C" and control group cells with floats of less than 0.013 cm. (Note: Ohmic bar "float" is the silicon material between the ohmic bar contact and the edge of the cell.) This added dimension along with the "pillow" effect caused by the required initial etching of the "CM" and "F" group (since they were supplied as 2 x 2's) caused test fixture "fingers" to just

barely make contact to the ohmic bar. This slight and variable increase in resistance when testing the cells caused the E-I curve to appear as if the cells were shunted, and in a few cases, severely so. After correcting the indexing on the test fixture, most of the "shunting" effect disappeared and repeatable readings and curves could be obtained. The few cells that still exhibited poor curve shapes could probably be attributed to the impurities incorporated in the silicon material.

As mentioned in the summary of Section 1, one lot of cells containing carbon, 10-F, was the only group where the average trend of electrical characteristics did not apply to all cells in the group. This lot contained two cells which, after the chemical polish etch processing step, showed large areas of striations on the cell surface. Inspection under a microscope revealed striations commonly associated with polycrystalline silicon. These two cells when tested, exhibited very low electrical output, 7.0 and 9.6 mW/cm², as compared to the other cells in the group which exhibited a nominal 15.5 mW/cm² and they also had the peak spectral response shifted approximately 200 nm toward shorter wavelengths than the balance of the lot.

The group with sodium as the incorporated impurity, lot 10 cm, showed no abnormality in electrical characteristics where conversion efficiency was a respectable 12.1%. However when the cells in the lot were tested for contact adherence all but three cells in the group of 12 cells showed drastic contact peeling. A check of control cells processed prior to and after Lot 10 cm showed no evidence of peeling indicating that the peeling on this lot may have been the direct result of the impurity dopant. The impurity level for sodium in this test lot was not available.

Tables I, II, and III contain the electrical data for the C, CM, and F groups. The ranges and average values of short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power (P_{max}) are given plus the number of cells in the various groups from which the data was extracted.

Table IV shows the various elements, the resistivity of the material, the average efficiency of the group based on total cell area and, whenever possible, the reported impurity concentration levels. As can be seen, no definite trend can be ascertained based on these results.

4.0 CONCLUSIONS

As has been reported throughout this program, it is very difficult to form any conclusions based on the data derived from these tests. Many other variables can influence the cell conversion efficiencies of the cells such as: 1) bulk resistivity, 2) segregation coefficients of the various elements, 3) surface finish which may be related to the impurity and its level of concentration, 4) impurity level variations from slice to slice and 5) whether the tang or seed end of the ingot was used. As can be seen, too many variables were not known during the program period to draw any firm conclusions. However some trends were clearly indicated. The first trend discovered indicates that most elements in impurity levels below 10^{13} atoms/cm³ did not drastically reduce conversion efficiencies.

However because the reported impurity levels were listed as "less than" or "greater than" some given level, it was indefinite as to what the actual impurity level was in the slices being processed.

Table 1 Electrical Summary*

(Group C)

Westinghouse/Dow Corning Crucible Grown Silicon

Subgroup	Impurity	Impurity Level (10^{15})	I_{sc} range (mA)	\bar{I}_{sc} (mA)	V_{oc} range (mV)	\bar{V}_{oc} (mV)	P_{max} range (mW)	\bar{P}_{max} (mW)	Size
1-C	--	--	66.6-65.6	66.2	576-574	575	30.6-29.8	30.3	7
2-C	Ni	0.5	64.5-61.4	62.7	577-568	575	29.8-28.0	29.2	9
3-C	Al	26.0	60.7-59.4	60.0	577-572	574	27.9-26.6	27.4	9
4-C	Zr	<.015	61.4-58.2	60.1	566-561	564	27.4-25.1	26.5	9
5-C	Cr	0.2	66.3-65.0	65.6	578-570	575	30.4-29.7	29.9	6
6-C	Ni	4.0	64.1-62.1	63.2	576-568	572	29.1-26.5	28.3	12
7-C	Fe	1.7	52.5-48.4	50.8	524-519	522	21.9-19.8	21.0	9
8-C	Al	34.0	52.2-49.6	50.9	550-548	549	22.7-20.7	21.9	12
9-C	Ti	.0036	61.8-59.6	60.8	567-563	566	27.7-26.9	27.3	12
10-C	Zr	<.025	60.3-59.3	60.0	558-554	557	26.5-25.9	26.3	10
11-C	V	.004	64.3-61.1	63.0	555-552	553	27.9-26.4	27.5	10
12-C	Mn	.013	69.7-65.1	67.3	580-578	579	32.5-30.4	31.4	10
13-C	Fe	.017	69.4-65.8	67.7	582-577	580	32.2-30.7	31.4	12
14-C	Mg	.32	67.5-65.3	66.5	579-572	576	31.1-30.1	30.5	13
15-C	Mn/Cu	1.3/1.7	65.2-59.0	62.3	567-556	561	29.4-26.4	28.0	13
16-C	Cr/Cu	1.0/1.7	59.8-56.3	57.9	546-537	541	25.6-23.7	24.4	12
17-C	Zr/Ti	<.015/4	39.9-37.8	38.8	497-493	495	15.2-14.3	14.7	13
18-C	Fe/Ti	.56/.05	47.1-44.5	45.8	523-518	522	19.1-18.1	18.6	11
19-C	Cr/Ni/Cu	3.0/.8/1.7	59.4-48.6	53.7	555-522	539	26.2-20.1	23.0	12
20-C	Mg	.003	68.5-66.3	67.4	584-578	581	32.2-30.7	31.5	13
21-C	Cu	17.0	67.5-64.1	65.8	577-572	575	31.1-29.4	30.1	12
22-C	Ti	.07	46.2-44.6	45.3	527-524	526	18.9-18.2	18.5	13
23-C	V	.0004	38.4-36.6	37.7	495-490	494	14.7-13.6	14.3	11
24-C	Cu	--	65.5-62.8	64.4	580-576	578	30.9-29.3	30.0	9
25-C	Ni	7.5	54.0-51.0	52.7	553-545	549	23.2-21.1	22.1	6
26-C	Ti	.00036	67.2-65.0	66.4	580-578	578	31.4-30.0	30.8	12
27-C	Cu/Ti	1.3/.36	67.2-63.7	65.9	576-570	573	30.8-29.4	30.1	13
28-C	Ti/V	.00036/.0004	59.2-56.5	58.3	552-549	551	25.8-24.4	25.3	13
29-C	Cr/Mn	1.0/1.3	51.0-47.6	49.4	518-509	514	20.6-18.7	19.8	13
30-C	Fe/V	.56/.07	50.3-47.1	49.2	523-517	522	20.7-19.2	20.2	10
31-C	Cu/Ni/Zr	1.7/.75/<.015	65.0-61.8	63.1	570-566	568	29.2-27.3	28.4	13
32-C	Cr/Fe/Ti	.65/.43/--	44.0-42.0	42.9	514-508	511	17.8-16.6	17.1	13
33-C	Cu	--	67.4-65.0	65.9	574-569	571	31.2-29.7	30.4	13

*1 x 2 cm specimens measured at 25°C under 135.3 mW/cm² (AMO spectrum)

Table 2 Electrical Summary*

Subgroup	Impurity	Impurity Level (10 ¹⁵)	I _{sc} Range (mA)	(Group CM)			P _{max} Range (mW)	P _{max} (mW)	Number of Cells
				I _{sc} (mA)	V _{oc} Range (mV)	V _{oc} (mV)			
1 CM	--	--	115 -117.1	116.0	612-617	615	48.8-56.7	54.6	13
2 CM	Cr	4.0	112 -115	113.5	610-618	616	48.6-57.1	55.2	13
3 CM	Ni	71.0	110.2-113.3	111.1	611-617	613	49.7-57	53.6	12
4 CM	Mn	12.0	108.8-114.2	111.4	617-620	619	54.1-57.8	56.0	12
5 CM	Fe	2.1	110.2-115.2	113.1	601-615	610	49.0-56.4	54.4	13
6 CM	C	74.0	118 -120.8	119.2	614-621	619	51.5-59.4	56.6	13
7 CM	Al	110.0	43.7- 50.6	47.9	514-535	527	16.6-20.9	19.2	12
8 CM	Ti	0.6	63.3- 67.5	66.3	541-545	544	26.6-28.8	28.1	9
9 CM	Zr	--	110.5-112.6	111.7	613-615	615	54.6-56	55.6	8
10 CM	Na ⁺	--	113 -115.8	114.3	613-616	615	55.4-57.1	56.3	12
11 CM	V	0.7	74.8- 79	77.6	564-568	567	32.3-36.2	35.2	11
12 CM	Mg	1.2	110 -114	111.6	615-618	616	53.4-55.7	54.4	12
13 CM	C/Ni	--	113 -115	113.9	592-615	611	33.3-55.8	51.5	7
14 CM	B/Pcomp	--	110.5-115.5	113.7	615-621	619	54.2-57.7	56.3	13

*1.85 cm² specimens measured at 25°C under 135.3 mW/cm² AMO spectrum

Table III

Electrical Summary*

Monsanto Float Zone Refined Silicon
(Group F)

Sub-group	Impurity	Impurity Level ($\times 10^{15}/\text{cm}^3$)	I_{sc} Range (mA)	Average I_{sc} (mA)	V_{oc} Range (mV)	Average V_{oc} (mV)	P_{max} Range (mW)	Average P_{max} (mW)	Number of Cells
1F	--	----	117.0-119.6	118.4	605-611	608	54.3-58.7	57.3	12
2F	Ni	15.0	113.8-117.0	114.9	619-623	621	55.5-58.2	57.1	12
3F	Fe	----	111.8-117.0	114.9	608-619	615	46.2-55.8	53.8	10
4F	Al	400.0	114.5-117.8	116.0	622-625	624	54.4-58.2	56.8	10
5F	Ti	----	75.7- 78.9	76.8	562-568	564	34.0-35.9	34.5	9
6F	Zr	----	111.0-116.8	114.3	618-623	620	55.1-59.4	57.5	12
7F	V	0.4	87.2- 89.3	88.0	584-585	585	40.5-41.9	41.3	8
8F	Mg	----	114.2-118.0	116.0	622-625	624	55.7-58.4	57.5	12
9F	Mn	1.5	113.7-115.9	114.7	497-618	599	(Note 1)	(Note 1)	10
10F	C	31.0	82.5-115.4	109.6	534-619	604	(Note 1)	(Note 1)	13
11F	Na	----	113.3-116.5	114.5	615-623	620	51.4-57.5	55.5	12
12F	Cu	----	113.8-116.6	115.4	607-624	621	41.9-57.2	54.4	13
13F	Cr	----	119.5-121.8	120.3	620-629	625	51.9-61.4	56.8	6+
14F	B/P-comp	----	113.8-116.6	115.5	625-627	626	56.7-58.6	57.6	11
15F	Ni/Mn/Mg	----	110.4-115.7	113.7	612-620	618	52.0-56.7	55.1	10
16F	Al	----	108.8-113.3	111.5	618-619	618	54.9-57.0	55.8	11

* 1.85 X 1.85 cm specimens measured at 25°C under 135.3 mW/cm² AMO spectrum.

+ Lot contained only seven (7) cells upon receipt from JPL.

Note 1 - Encountered test equipment problems; data may not be valid as reported.

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Table IV
Impurity Groups C, CM and F*

Impurity	Parameter	C Group	CM Group	F Group
Nickel	Resistivity	4.1 ohm-cm	0.5 ohm-cm	0.5 ohm-cm
	Efficiency	11.9%	11.5%	12.2%
	Impurity level	5.0×10^{14}	7.1×10^{16}	1.5×10^{16}
	Resistivity	3.9 ohm-cm		
	Efficiency	11.6%		
	Impurity level	4.0×10^{15}		
	Resistivity	4.2 ohm-cm		
	Efficiency	8.2%		
	Impurity level	7.5×10^{15}		
Iron	Resistivity	5.9 ohm-cm	0.5 ohm-cm	0.5 ohm-cm
	Efficiency	8.6%	11.7%	11.5%
	Impurity level	1.7×10^{15}	2.1×10^{15}	N.D.
Aluminum	Resistivity	2.9 ohm-cm	0.15 ohm-cm	0.5 ohm-cm
	Efficiency	11.2%	4.1%	12.2%
	Impurity level	2.6×10^{16}	8.3×10^{18}	4.0×10^{17}
	Resistivity	2.2 ohm-cm		0.4 ohm-cm
	Efficiency	8.9%		12.0%
	Impurity level	3.4×10^{16}		-----
Titanium	Resistivity	4.8 ohm-cm	0.48 ohm-cm	0.53 ohm-cm
	Efficiency	11.1%	6.0%	7.4%
	Impurity level	3.6×10^{12}	6.0×10^{14}	5.2×10^{14}
	Resistivity	4.2 ohm-cm		
	Efficiency	6.8%		
	Impurity level	7.0×10^{13}		
	Resistivity	4.2 ohm-cm		
	Efficiency	11.4%		
	Impurity level	3.6×10^{11}		
Zirconium	Resistivity	4.5 ohm-cm	0.57 ohm-cm	0.46 ohm-cm
	Efficiency	9.7%	11.9%	12.3%
	Impurity level	$< 1.5 \times 10^{13}$	N.D.	-----
	Resistivity	4.6 ohm-cm		
	Efficiency	9.7%		
	Impurity level	$< 2.5 \times 10^{13}$		
Vanadium	Resistivity	4.1 ohm-cm	0.53 ohm-cm	0.47 ohm-cm
	Efficiency	10.1%	7.5%	8.9%
	Impurity level	4.0×10^{12}	7.0×10^{14}	5.6×10^{14}
	Resistivity	4.8 ohm-cm		
	Efficiency	5.3%		
	Impurity level	4.0×10^{11}		

(continued)

Table IV (cont'd.)
Impurity Groups C, CM and F*

Impurity	Parameter	C Group	CM Group	F Group
Magnesium	Resistivity	4.2 ohm-cm	0.54 ohm-cm	0.44 ohm-cm
	Efficiency	11.2%	11.7%	12.3%
	Impurity level	3.2×10^{14}	1.2×10^{15}	5.3×10^{16}
	Resistivity	3.9 ohm-cm		
	Efficiency	11.6%		
	Impurity level	3.0×10^{12}		
Manganese	Resistivity	4.2 ohm-cm	0.45 ohm-cm	0.46 ohm-cm
	Efficiency	11.5%	12.0%	8.7%
	Impurity level	1.3×10^{13}	1.2×10^{16}	1.5×10^{15}
Carbon	Resistivity		0.58 ohm-cm	0.48 ohm-cm
	Efficiency		12.1%	9.2%
	Impurity level		7.4×10^{16}	3.1×10^{16}
Chromium	Resistivity	4.4 ohm-cm	0.57 ohm-cm	0.47 ohm-cm
	Efficiency	11.0%	11.8%	12.2%
	Impurity level	2.0×10^{14}	4.5×10^{15}	2.6×10^{15}
Copper	Resistivity	4.0 ohm-cm		0.43 ohm-cm
	Efficiency	11.1%		11.7%
	Impurity level	1.7×10^{16}		3.1×10^{16}
	Resistivity	3.95 ohm-cm		
	Efficiency	11.1%		
	Impurity level	-----		

- * C Group = Westinghouse/Dow Corning crucible grown silicon
 CM Group = Monsanto crucible grown silicon
 F Group = Monsanto float zone refined silicon

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The second trend discovered was the a-parent neutralizing behavior of copper in binary and ternary systems that appear to alleviate the degradation characteristics of the impurity. However as mentioned earlier in this report, a possibility of slice mixup for the Cu/Ti lot may negate this observed trend. Until such time that a second ingot is grown, sliced and processed through the standard processing technique, this behavior cannot be confirmed. However with copper as the only impurity present, indications are (see Table IV) that a high concentration of copper can be tolerated without appreciable degradation of cell efficiency.

5.0 RECOMMENDATIONS

It is recommended that additional work be done with binary systems containing copper and other impurities to see if the trend observed on this program is real. Perhaps other elements that show little cell conversion degradation may also act in a beneficial way in regard to cell efficiency in conjunction with other impurities. An interesting investigation would be to process into solar cells, binary and ternary ingots with those impurities that do not appear to degrade cell efficiency. Or, knowing which impurities to avoid in silicon processing, grow ingots with nondegrading impurities as economically as possible and manufacture solar cells from these ingots. Some form of polycrystalline silicon should also be investigated again, with the nondegrading impurities added, to see if poly material can be used as a source of cheap silicon in large scale solar arrays.

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